12

Theoretical Studies on Ionospheric Irregularities and Ion Diode Performance

Final Technical Report on ONR Grant # N00014-89-J-1770

Period: January 1, 1989 - August 31, 1993

Technical Monitor: Dr. C. Roberson

Principal Investigator: Prof. R.N. Sudan

LABORATORY OF PLASMA STUDIES
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March 11, 1994

Dr. Charles W. Roberson, Technical Monitor
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A

Dear Dr. Roberson:

Please find enclosed 3 copies of the Final Technical Report on the research work performed by scientists of the Laboratory of Plasma Studies, Cornell University under ONR Grant # N00014-89-J-1770. Please feel free to contact me if you have any comments.

Sincerely,

R.N. Sudan
Principal Investigator

Enclosures

cc: Admin. Grants Officer, ONR
Director, NRL
✓ Defense Technical Information Center

RNS/scj

This report covers the activities engaged by members of the Laboratory of Plasma Studies, Cornell University under ONR Grant # N0014-89-J-1770 for the period January 1, 1989 to August 31, 1993.

Personnel

The personnel supported in part by this Grant are listed below:

Principal Investigator

Professor R.N. Sudan

Postdoctoral/Research Associate

Dr. A. Hamza

Visiting Scientist

Academician A. Gurevich, Lebedev Institute, Moscow, Russia

Graduate Research Assistants

A.A. Thoul

B. Oliver

M. Rilee

P. Schuck

Technical Progress Accomplished (1/1/89 - 8/31/93)

The work accomplished is divided into three parts and the abstracts of the papers published are given below. The abstracts of Conference papers are appended.

I. Ionospheric Physics

1. "Numerical Simulations of Large-Scale Plasma Turbulence in the Daytime Equatorial Electrojet", C. Ronchi, R.N. Sudan and D.T. Farley, *Journal of Geophys. Res.* **96** No. A12, 21,263 - 21,279, Dec. 1, 1991.

Abstract

We present numerical simulations of the large-scale electron density irregularities in the daytime equatorial electrojet driven by the gradient drift instability. The nonlocal nonlinear two-fluid equations are integrated numerically with scales ranging from about 10 km to less than 100 m directly resolved on a 128 x 128 grid, while the effects of the small subgrid scales are included with the use of anomalous electron mobility and diffusion coefficients [*Ronchi et al., 1990a*]. The instability evolves to a state in which the perturbations propagate primarily in the east-west direction with a typical horizontal wavelength of about 2 km. The output of the numerical simulations does not indicate the presence of a significant anisotropy in the power spectrum of the irregularities in the plane perpendicular to the ambient magnetic field, in contrast to the marked differences observed in physical space between the vertical and horizontal dynamics. The one-dimensional integrated density and electric field power spectra have a power law dependence with a power index ranging between -2.5 and -1.2. The numerical results are compared with in situ rocket observations by probing the simulation region along different flight paths, following both eastward and westward trajectories. Electron vertical turbulent velocity distributions are computed from the code output and are contrasted with radar backscatter data. The features typical of the 3-m type 2 echoes (such as the broadening and asymmetry in the frequency power spectra) are also present in the computed distributions, indicating that during weak electrojet conditions the small-scale structures act as tracers of the large-scale electric field variations. A conclusion of particular note is that a purely linear nonlocal analysis (valid for wavelengths $\lambda \approx 1$ km) leads to the result that all perturbations are eventually damped, either by shear and

then diffusion or by recombination. The inclusion of nonlinear effects, however, restores the instability. In the strongly turbulent regime a nonsteady saturated state is reached, whereby the linear convection of energy via shear to high wavenumbers is countered by the nonlinear modification of the equilibrium density and electric field gradients and by mode coupling of shorter wavelengths back to long.

2. "An Almost Two-Dimensional Approach to Type 2 Irregularities in the Equatorial Electrojet", J.M. Albert, P.L. Similon and R.N. Sudan, *Journal of Geophys. Res.* Vol. **96** No. A9, 16,015-16,020, Sept. 1, 1991.

Abstract

A recently developed theory of "almost two-dimensional" turbulence (Albert et al., 1990) is applied to $E \times B$ fluctuations in the E region equatorial electrojet. This theory of plasma turbulence in an external magnetic field extends strictly two-dimensional theory (e.g., Sudan and Keskinen, 1979) to include weak phase variations along the magnetic field. Based on the direct interaction approximation of Kraichnan (1959), it describes the tendency of spectral energy to transfer nonlinearly towards modes with high $k_{\parallel}$ despite strong linear damping of these modes. Here, we discuss application of this theory to the aspect angle $k_{\parallel}/k$ of fluctuations at 3-m scales, for which radar backscatter measurements have been made (Kudeki and Farley, 1989). Allowing for uncertainty in characterizing the plasma turbulence, we find good agreement except at the lowest altitudes of the electrojet.

3. "Three-wave Interactions and Type II Irregularities in the Equatorial Electrojet", J.M. Albert and R.N. Sudan, *Phys. Fluids B* **3** (2), February 1991.

Abstract

A spectral description of a model of convective turbulence in the

E region of the equatorial ionosphere is considered. It is demonstrated that three complex modes are sufficient to generate a stochastic steady state, in a manner analogous to similar models of the Euler equation and drift waves. Complex terms in the nonlinear coupling coefficient are retained that are usually dropped on the basis of large kL, where L is the density gradient scale length. In addition, some parallel damping is included. Parameters that lead to a stochastic steady state are then found by explicitly solving for the wave vectors that reproduce growth rates and nonlinear coupling terms from a known stochastic case of a drift wave model.

The above three studies were jointly supported by ONR and NSF.

II. Ion Diodes, Magnetic Insulation, Plasma Opening Switches

1. "Two-Dimensional Electron Flow in Pulsed Power Transmission Lines and Plasma Opening Switches", B.W. Church, D.W. Longcope, C.-K. Ng and R.N. Sudan, , in *Proceedings of the Thirteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research* held by the International Atomic Energy Agency in Washington, D.C., 1-6 October 1990.

Abstract

The operation of magnetically insulated transmission lines (MITL) and the interruption of current in a plasma opening switch (POS) are determined by the physics of the electrons emitted by the cathode surface. A mathematical model describes the self-consistent two-dimensional flow of an electron fluid. A finite element code, FERUS has been developed to solve the two equations which describe Poisson's and Ampère's law in two dimensions. The solutions from this code are obtained for parameters where the electron orbits are considerably modified by the self-magnetic field of the current. Next, the self-insulated electron

flow in a MITL with a step change in cross-section is studied using a conventional two-dimensional fully electromagnetic particle-in-cell code, MASK. The equations governing two-dimensional quasi-static electron flow are solved numerically by a third technique which is suitable for predicting current interruption in a POS. The object of the study is to determine the critical load impedance, Z_{CL}, required for current interruption for a given applied voltage, cathode voltage and plasma length.

2. "Electron and Hall Magnetohydrodynamics and Magnetic Field Penetration in a Plasma", L.I. Rudakov, C.E. Seyler and R.N. Sudan, *Comments Plasma Phys. Controlled Fusion*, 1991, Vol. 14, No. 3, pp. 171-183.

Abstract

This Comment emphasizes the effect of Hall currents in magnetohydrodynamics; in particular its role in the penetration of magnetic field in a magnetized plasma over distances of order c/ω_i (ω_i: ion plasma frequency) ahead of a magnetic piston. Applications to plasma opening switches, beam injection and liner implosions are discussed.

3. "A Fluid Model for Electron Dynamics in the Vacuum Gap of a Plasma Opening Switch", C.-K. Ng and R.N. Sudan, *J. Appl. Phys.* **69** (1), 1 January 1991.

Abstract

A two-dimensional fluid model is developed to study the equilibrium flow of electrons in the vacuum gap between the cathode and the plasma of a plasma opening switch. The dynamics of electron flow in the vacuum gap region is illustrated by the distributions of the magnetic field, the electrostatic potential, and the electron density. The dependencies of the switch current and its interruption in the vacuum gap on the dimensions of the vacuum gap, the load impedance, and the electrostatic potential across the gap are investigated. The two-dimensional

aspect of the electron flow in the vacuum gap and its effects on the performance of a plasma opening switch are emphasized.

4. "Ion Beam Divergence from Unstable Fluctuations in Applied-B Diodes", R.N. Sudan and D.W. Longcope, *Phys. Fluids B* **5** (5), May 1993.

Abstract

An electron plasma oscillation driven unstable by ion streaming is identified with the low-frequency mode observed in QUICKSILVER [*Computational Physics*, edited by A. Tenner (World Scientific, Singapore, 1991), pp. 475-482] numerical simulations. This mode heats the electrons along the magnetic field and is ultimately stabilized by the thermal spread. A quasilinear theory determines the saturation level of the fluctuations, the ion divergence, and the ion energy and momentum spread as they exit the diode. The ion divergence is predicted to be independent of the ion mass for fixed diode voltage and scales as the product of the effective gap and the ion beam enhancement factor over Child-Langmuir current.

The above four studies were jointly supported by ONR and Sandia Laboratories, Albuquerque, NM.

III. Subgrid Modeling in Numerical Computations and Misc. Research

1. "Renormalization Group Analysis of Reduced Magnetohydrodynamics with Application to Subgrid Modeling", D.W. Longcope and R.N. Sudan, *Phys. Fluids B* **3** (8), August 1991.

Abstract

The technique for obtaining a subgrid model for Navier-Stokes turbulence by Yakhot and Orszag [J. Sci. Comput. **1**, 3 (1986); Phys. Rev. Lett. **57**, 1772 (1986)], based on renormalization group analysis (RNG), is extended to the reduced magnetohydrodynamic (RMHD)

equations. A RNG treatment of the Alfvén turbulence (perpendicular scale $k_{\perp}^{-1} \ll k_{\parallel}^{-1}$ parallel scale) supported by the RMHD equations leads to effective values of the viscosity and resistivity at large scales, $k \rightarrow 0$, dependent on the amplitude of turbulence. When the RNG analysis is augmented by the Kolmogorov argument for energy cascade the effective viscosity and resistivity become independent of the molecular quantities. This leads to a "universal" subgrid model, which all models approach at the largest scales. A self-contained system of equations is derived for the range of scales, $0 < k < K$, where $K = \pi/\Delta$, is the maximum wave number for a grid size Δ. In this system the resistive and viscous dissipation is represented by differential operators, whose coefficients depend upon the amplitudes of the large-scale quantities being computed.

This study was jointly supported by ONR, NSF and NASA.

1. "Green's Functions in WKB Approximation", D. Pfirsch and R.N. Sudan, *J. Math. Phys.* **32** (7), July 1991.

Abstract

A systematic technique based on a variational principle is developed is developed for obtaining WKB Green's functions for a non-Hermitian set of inhomogeneous, nonstationary differential equations in a space of arbitrary dimensions. A key element in this technique involves the use of the Van Vleck determinant for the amplitudes of WKB functions.

This study was jointly supported by NSF and ONR. (In the paper there is a typo in the acknowledgement of the ONR support.)

Abstract Submitted for the Thirty-fourth Annual Meeting
. (Division of Plasma Physics)
November 16-20, 1992, Seattle, WA

Category Number and Subject 6.3 Accelerator schemes

X Theory ___ Experiment

Electron Flow in Positive-Polarity Multigap Inductive Accelerators*. B. W. Church and R. N. Sudan, Cornell University — We study the electron flow in multi-gap inductive accelerators, such as Hermes III operating in positive polarity by numerical simulation and modeling. The objective of this work is to determine the operating principles such that an optimally efficient design of the Hermes-type machine can be achieved for intense ion beam generation. We employ a 2-D fully electromagnetic particle in cell code, MASK†, to represent the electrons emitted in the accelerating gaps and their dynamics. The simple theory of magnetic insulation[1] has to be extended to such multi-component electron flows. MASK has been used to simulate an accelerator with a small number of gaps for various load impedances. A simple theoretical model for multi-component electron flows has been developed to predict the distribution of electron flows. Individual diamagnetic electron vortices observed in the electron flows are compared to a self-consistent solution of a cylindrically symmetric fluid model which shows good agreement with data observed from the runs. However these vortices tend to cause mixing of the launched electrons. We have therefore modeled the multi-component electron flow with only two components. The model will be compared with existing multi-component models[2] and simulations.

1. MENDEL, C.W., SEIDEL D.B., ROSENTHAL, S.E., Laser and Particle Beams, vol. 1, part 3, p.311.
2. ROSENTHAL, S.E., IEEE Transactions on Plasma Science, vol. 19,no. 5, October 1991.

*Research supported by Sandia National Laboratory, under Contract No. 63-4881 and by ONR contract N00014-89-J-1770.
†MASK was provided by Adam Drobot of Science Applications International Inc.

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Abstract Submitted for the 1991 APS Annual Meeting
(Division of Plasma Physics)
November 4-8, 1991, Tampa, FL

Category Number and Subject 5.7/High current, high energy accelerators

☒ Theory ☐ Experiment

Electron Flow in Positive-Polarity Multigap Inductive Accelerators* B.W. Church, R.N. Sudan, *Cornell University* - We study the electron flow by numerical simulation and modeling in multi-gap inductive accelerators, such as Hermes III operating in positive polarity. The objective of this work is to determine the operating principles such that an optimally efficient design of the Hermes-type machine can be achieved for intense ion beam generation. We employ a 2-D fully electromagnetic particle in cell code, MASK†, to represent the electrons emitted in the accelerating gaps and their dynamics. Because the electrons emitted in different gaps have different energies and canonical momenta, the simple theory of magnetic insulation [1] has to be extended to such multi-component electron flows. In order to understand the effects of load impedance on the distribution of electron flows in the multi-gap accelerator and on the coupling of power to the load, MASK has been used to simulate an accelerator with a small number of gaps for various load impedances. In addtion, a simple theoretical model for multi-component electron flows will be developed to predict the distribution of electron flows and will be compared with the results of the numerical simulations.

[1] MENDEL , C.W., et al., Laser and Particle Beams, vol. 1, part 3, p.311.

*Research supported by SNL, Albuquerque, under Contract No. 63-4881 and by ONR contract N00014-89-J-1770.

†MASK was provided by Science Applications International Inc.

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Abstract Submitted for the Thirty-second Annual Meeting
(Division of Plasma Physics)
November 12-16, 1990

Category Number and Subject________________

_X_ Theory ___Experiment

"**A Two-Dimensional Model for Electron Flow in High Power Magnetically Insulated Transmission Lines and Plasma Opening Switches**," B.W. CHURCH, D.W. LONGCOPE and R.N. SUDAN, Cornell University,* – The purpose of this work is to develop a two-dimensional self consistent model for equilibrium electron flow in high power magnetically insulated transmission lines and plasma opening switches. A mathematical fluid model for equilibrum electron flow reduces to one-dimensional Child-Langmuir flow in the limit that the magnetic field can be ignored and in the other extreme to the one-dimensional limit of insulated relativistic Brillouin flow. The model consists of a pair of partial differential equations for the potential and the vorticity in the electron flow. The equations are implemented in a finite element code with an adaptive triangular mesh called Ferus. Using Ferus, uninsulated electron flow equilibria in a parameter regime bordering the Child-Langmuir limit were found that match equilibria produced by MASK, a fully electromagnetic particle in cell code. We will investigate equilibria in a regime bordering on the insulated limit using both MASK and Ferus.

* Work supported by the Plasma Physics Division, NRL, Washington, DC 20375-5000 under ONR contract N00014-89-J-1770 and Sandia Contract # 63-4881.

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Abstract Submitted for the Thirty-second Annual Meeting
(Division of Plasma Physics)
November 12-16, 1990

Category Number and Subject 5.15.1

X Theory ___ Experiment

"Fluid simulation of electron dynamics and current interruption in the vacuum gap of a plasma opening switch," C.-K. NG and R. N. SUDAN, Cornell University,*, – A two-dimensional equilibrium fluid model[1] is developed to study the electron dynamics in the vacuum gap between the cathode and the plasma of a POS. Electrons at the cathode are emitted in a Child-Langmuir fashion applied close to the cathode. The fluid equations are solved self-consistently to obtain the electron flow pattern, the distributions of electron density, magnetic field and electrostatic potential in the vacuum gap. The switch current flowing across the vacuum gap depends on the load impedance, the aspect ratio of the gap and the potential difference across the gap. The interruption of the switch current as functions of these quantities are investigated.

* Work supported by the Plasma Physics Division, NRL, Washington, DC 20375-5000 under ONR Grant N00014-89-J-1770 and by Sandia Contract # 63-4881.

[1] R. N. Sudan and P. L. Similon, Report # LPS 88-5, Laboratory of Plasma Studies, Cornell University (1988).

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Abstract Submitted for the Thirty-second Annual Meeting
(Division of Plasma Physics)
November 12-16, 1990

Category Number and Subject________________

___Theory ___Experiment

"Numerical Simulations of Nonlocal Gradient-Drift Turbulence," C. RONCHI, R. N. SUDAN, Cornell University* and P.L. SIMILON Yale University, – Numerical simulations of the nonlocal nonlinear two fluid equations describing the large scale dynamics of the equatorial electrojet, are presented. Scales ranging from 10 km to ~100m are directly resolved on a 128 × 128 grid, while the effects of the smaller subgrid scales are included with the use of anomalous electron mobility and diffusion coefficients.[1] The output of the numerical simulations does not indicate the presence of a strong power anisotropy for the irregularities in the plane perpendicular to the ambient magnetic field. The numerical results are compared with both rocket and radar observations. After an initial transient during which energy is efficiently transferred via linear shearing to the small scales, a saturated state is achieved by constantly repopulating the locally growing long wavelength modes via nonlinear coupling of the short scale modes. This complex interplay which takes place in momentum space bet[illegible]n linear convection, due to velocity shear, and nonlinear scattering, due to mode coupling, is analyzed and further discussed with the use of a nonlinear model equation.

1. C. Ronchi, R.N. Sudan and P.L. Similon, J. Geophys. Res. 95, 189(1990).

*Work supported by NSF 87-12710 and ONR N00014-85-K-0212.

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Abstract Submitted for the Thirty-first Annual Meeting
Division of Plasma Physics
November 13–17 1989

Category Number and Subject 1.8/T

[X] Theory [ ] Experiment

Renormalization Group Analysis of Drift Wave Turbulence.* A. M. HAMZA, and R. N. SUDAN. *Cornell University.* — The Hasegawa-Mima (HM) equation[1] describes the most simple case of drift wave turbulence, neglecting the nonadiabatic response of the electrons. The Terry-Horton (TH) equation[2] is a modified version of the HM equation, modeling the nonadiabatic response of the electrons. We present a detailed dynamical renormalization-group (RNG) analysis of these equations (HM, and TH) subject to random noise. The RNG methods are used to study the effect of the small scale drift wave potential structures on the long time behavior of the long wavelength fluctuations. This effect may be interpreted as an effective viscosity. This enhanced energy dissipation can be incorporated into the equation by renormalizing the linear dielectric function, and therefore leading to a self similar form, which is then used to evaluate the ω integrated energy spectrum.

* Work supported in part by the Plasma Physics Division, Naval Research Laboratory under ONR Grant N00014-89-J-1770 and National Science Foundation Grant 8712710.

[1] A. Hasegawa and K. Mima, Phys. Rev. Lett. 39, 205 (1977).

[2] W. Horton, Phys. Fluids 29 (5), 1986.

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Abstract Submitted for the Thirty-first Annual Meeting
Division of Plasma Physics
November 13–17 1989

Category Number and Subject 1.11/T

[X] Theory [ ] Experiment

The Nonlinear Description of a Plasma Maser.* K. MURUKESSAPILLAI, *Sri-Lanka*, A.M. HAMZA, *Cornell University*. — The plasma maser consists of a single electromagnetic wave interacting with an unstable plasma[1]. Multiwave interactions do not occur in this case. Therefore we only consider the evolution of the single wave-plasma system. All the nonlinear methods describing the single wave-plasma interaction start with the evaluation of the current density in the presence of the wave by the method of characteristics. Hereafter, the various methods diverge in detail although the underlying principle for all these methods is the same. An amplification of the incident wave will occur as long as the real part of the nonliear conductivity remains negative. This is equivalent to the condition $\mathbf{J} \cdot \mathbf{E} < 0$. This is implied by Maxwell's equations of classical electrodynamics. Obviously, this is equivalent to the imaginary part of the susceptibility being negative. In this sense the nonlinear description of the plasma maser is similar to the one used in the semi-classical theory of lasers, except that here the active medium is also described by classical mechanics. We have evaluated $\mathbf{J} \cdot \mathbf{E}$, and analyzed the conditions under which it becomes negative, and a nonlinear criterion for masing is therefore derived.

* Work partially supported by the plasma physics division, Naval Research Laboratory under ONR Grant N00014-89-J-1770 and National Science Foundation Grant 8712710.

[1] K. Murukessapillai, J. Appl. Phys. 62, 9 (1987).

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Abstract Submitted for the Thirty-first Annual Meeting
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Category Number and Subject 1.8/T & 6.1/T

[X] Theory [ ] Experiment

Numerical Simulations of Large Scale Turbulence in the Equatorial Electrojet.* C. RONCHI and R. N. SUDAN, *Cornell University;* P. L. SIMILON *Yale University* — A two dimensional mixed pseudospectral - finite difference code is used to simulate the large scale plasma turbulence in the equatorial ionospheric E region. The time evolution of the density and potential perturbations with wavelengths ranging from a few kilometers to about one hundred meters are directly simulated by integrating the nonlinear, nonlocal, two fluid equations.[1] The effect of the small scale, subgrid modes is included into the large scale equations via an enhanced Pedersen mobility and diffusion, obtained through a quasilinear treatement of the small wavelength electron equations.[2] The results of the numerical simulations are discussed and compared with rocket and radar observations of electrojet irregularities.

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* Work supported in part by the Plasma Physics Division, Naval Research Laboratory, under ONR Contract N00014-85-K-0212 and the National Science Foundation, Atmospheric Sciences Section, under NSF Grant 87-12710.

1 C. Ronchi et al.,J. Geophys. Res. 94, 1317 (1989).

2 C. Ronchi et al., E.O.S. Trans. AGU 69, 1344 (1988).

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Electron Flow in Positive-Polarity Multigap Inductive Accelerators*

B.W. Church and *R.N. Sudan*
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Abstract

We study the electron flow in multi-gap inductive accelerators, such as Hermes III operating in positive polarity by numerical simulation and modeling. The objective of this work is to determine the operating principles such that an optimally efficient design of the Hermes-type machine can be achieved for intense ion beam generation. We employ a 2-D fully electromagnetic particle in cell code, MASK†, to represent the electrons emitted in the accelerating gaps and their dynamics. Because the electrons emitted in different gaps have different energies and canonical momenta, the simple theory of magnetic insulation[1] has to be extended to such multi-component electron flows.

In order to understand the effects of load impedance on the distribution of electron flows in the multi-gap accelerator and on the coupling of power to the load, MASK has been used to simulate an accelerator with a small number of gaps for various load impedances. For load impedances below the self-limited impedance of the last segment of the accelerator, the electron flow in both segments is well insulated. The overall current efficiency is over 90% and is insensitive to the load impedance. Beyond the self-limited impedance, the current efficiency decreases rapidly with increasing load impedance. Because of this rapid decrease in efficiency, the power delivered to the load also falls off rapidly as load impedance is increased. To better understand these results, a simple theoretical model for multi-component electron flows is being developed to predict the distribution of electron flows. The model will be compared with existing multi-component models[2] and simulations.

For both high and low impedance loads the electron flow from the leading edge of each cathode is unsteady, producing an intermittent train of electron vortices. These vortices are not circular but elongated with an aspect ratio near one half and are slightly diamagnetic. The center of each vortex $\mathbf{E} \times \mathbf{B}$ drifts along with the local electron flow. In each vortex, electrons $\mathbf{E} \times \mathbf{B}$ drift about the vortex center along the potential contours of the vortex's self-electric field in a reference frame moving with the vortex center. These vortices were compared to a simple cylindrically symmetric fluid model which showed coarse agreement with data observed from the runs. The model will be extended to include 2-dimensional effects and the observed distribution of electron energies in the vortex.

1. MENDEL, C.W., SEIDEL D.B., ROSENTHAL, S.E., Laser and Particle Beams, vol. 1, part 3, p.311.
2. ROSENTHAL, S.E., IEEE Transactions on Plasma Science, vol. 19,no. 5, October 1991.

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